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NAVAL RESEARCH

REVIEWS

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FILE

Walter L. Clearwaters

One of the Navy's leading experts on the design of submarine sonar systems and the applications of sonar techniques to subsurface operations is Walter L. Clearwaters, who has had a distinguished career in research and development work in underwater acoustics. In 1943 he joined the staff of the Columbia University Division of War Research as a research engineer in Columbia's New London laboratory which, with the Harvard University Underwater Sound Laboratory, formed one of the predecessor facilities of the present Naval Underwater Systems Center. Since the Navy assumed control of the New London laboratory in 1945 he has served successively as head of the Submarine Sonar Division and the Systems Department, Chief of Research and Development at the New London laboratory and Director of Plans and Analysis. In addition, he has had responsibility for the duties of the Technical Director of the Center for the past year. Among his accomplishments, Mr. Clearwaters devised the "Clearwaters' Plot" for deriving from sonar data an optimum torpedo firing time, and it was largely owing to his technical expertise that the BQQ multifunction submarine sonar suit was developed. He was the 1969 recipient of the American Society of Naval Engineers Solberg Award, and he holds a number of patents for inventions applying to electrostrictive transducers and sonar systems.

The Role of the Naval Underwater Systems Center

Combining the functions of a research laboratory with those of an engineering center devoted to Fleet readiness, the Naval Underwater Systems Center (NUSC) was officially formed in 1970 through the merger of the Navy Underwater Sound Laboratory in New London, Connecticut, and the Naval Underwater Weapons Research and Engineering Station at Newport, Rhode Island. Each of these predecessor establishments has a long history of contribution in underwater research and technology. With a staff of over three thousand, including some 170 resident military program personnel intimately involved in the technical effort, NUSC serves as a leading facility for advancing and applying undersea technology to meet the challenges of the times.

The Center has made wide-ranging contributions to the solutions of problems of undersea warfare and to the fields of oceanography and ocean engineering, and its professional interests are demonstrated by many significant accomplishments. NUSC has been a pioneer in a number of areas, including sonar system development, the invention of the underwater telephone for submarine-to-submarine and submarine-to-surface communication, several deep-ocean engineering "firsts," and the development of mobile acoustic targets, new torpedoes and torpedo-launch systems.

Today, the Center operates two principal laboratory complexes in Newport and New London with a major undersea test and evaluation center at Andros Island in the Bahamas, and other facilities and field stations in Bermuda, Florida, New York, and New England. Through an exchange scientist program NUSC is represented at the New Zealand Defence Research Establishment; Royal Australian Navy Experimental Laboratory; Admiralty Underwater Weapons Establishment, England; and SACLANT ASW Weapons Research Center, Italy. Resident representatives are assigned to major Fleet ASW commands in Naples (Italy), San Diego, Pearl Harbor, Norfolk, New London, and Newport. In addition, the Center has some 75 technical persons in the field full time, dispersed throughout the world where the Fleet operates, engaged in experimental and scientific work on new systems or providing engineering support for in-service equipments.

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*This article was prepared by L. D. Wyld of the Special Projects Staff of the Naval Underwater Systems Center.

In support of its assigned mission, to plan and conduct research and development, test and evaluation of underwater combat systems, the Center utilizes its expertise, facilities and funding to evolve systems with complete operational capabilities, including communication, detection, launching, fire control, and ordnance. This mission is expressed in well-defined research and development objectives. Foremost among these are complete sonar detection, attack, and communication systems for submarine forces; anti-submarine detection systems for surface craft; and sonar surveillance systems for defense (Figure 1).

The submarine and surface ship sonar programs of NUSC provide the Navy with the latest developments in sonar systems. In addition, the Center provides technical direction and support to upgrade Fleet effectiveness in acoustic search, localization, tracking, and intercept by providing improvements and additions to onboard systems, many of which were originally developed at NUSC. The Center has major responsibilities for developing and improving the telecommunications

Figure 1–NUSC maintains the Dodge Pond Acoustic Measurements Facility at Niantic, Conn., for calibrating and testing underwater sound transducers, arrays, and sonar systems.

for command and control of submarines, and NUSC is a recognized leader in the development of antenna systems for all types of submarine use (Figure 2). Through corollary work in transducer research, development, and engineering, the Center also contributes to the continued improvement of equipment to meet today's increased sonar requirements.

Equally important Center activities are devoted to underwater combat systems research, development, test and evaluation, and ASW ordnance research. NUSC engineers and scientists are experts in the field of combat systems control—the complex electronic equipment that translates sensor data about target range, course, and speed into weapon orders and setting. In this important area, the Center has design cognizance or service engineering responsibilities for all existing torpedo and ASW missile fire control systems. At the same time it is involved in the development of advanced fire control subsystems for new submarines (Figure 3).

To provide essential support to weapon advances, weapon launching and propulsion systems must also be continuously investigated and developed. Recent achievements in electric torpedo

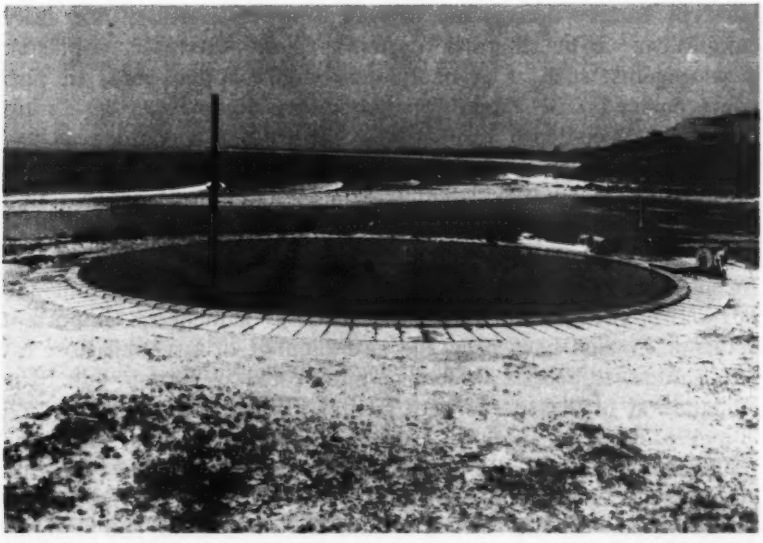

Figure 2—Submarine radio antennas and integrated communications systems are developed and tested at NUSC's unique test facility on Fishers Island. This tidal pond is the principal facility for testing buoyant cable antennas. There is no other such facility known.

Figure 3–Systems Analysis Laboratory. This general purpose simulation facility makes possible realistic evaluation of concepts before recommending their incorporation into new shipborne combat systems.

propulsion include a substantial increase in energy-density through pile-type battery design, and new, high power electric motors fully competitive with thermal systems. New thermal propulsion developments, such as Wankel rotary engine applications, are also being pursued. The Propulsion Laboratory complex at the Center includes a deep-depth torpedo test facility and a component test facility, with a staff comprised of a systems analysis group and research groups in fuels, chemistry, noise reduction, and materials (Figure 4).

NUSC has design cognizance and technical direction responsibility for all in-service torpedo tubes–both submarine and surface ship–and for anti-submarine rocket (ASROC) launchers. Important accomplishments have been the development of a flexible hose for wire-guided torpedoes which permits torpedo launch and wire guidance at higher speeds with greater submarine maneuverability, and the development of a turbine pump ejection system as a replacement for the reciprocating or ram torpedo tube ejection system. Center engineers are also involved in developing control cables needed for fire control system communication, and studying design requirements for launchers completely external to a submarine pressure hull.

A third major focus at NUSC is that of Fleet readiness, and service engineering to support the Fleet is a primary concern of the Center.

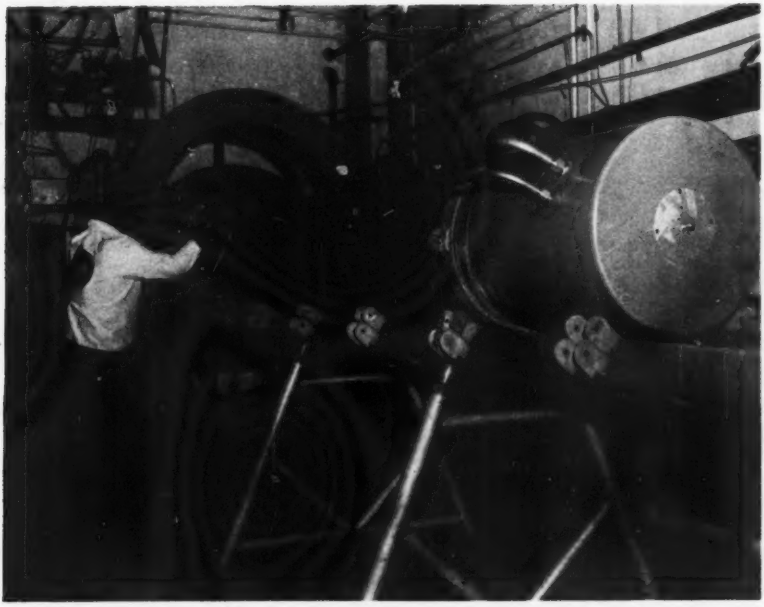

Figure 4–NUSC has the unique capability for system testing of an entire submarine-launched torpedo. In this photograph a technician is preparing a torpedo for total depth testing in the Center's propulsion test facility.

Quick response to the solution of problems with in-service systems has top priority. The Center also develops and manages programs which assure the Fleet effective system maintenance and logistics through ship trials, training, and facilities. Maintenance data and firing reports feedback are used for design improvements, modification of procedures, and improved logistic support.

Given these primary functions of the Center, and the necessity to assure the successful operability of all systems in the real world, considerable attention is also paid to the ocean sciences and ocean engineering. Center scientists make worldwide scientific cruises to explore the energetics of wind wave motion, temperature variations in space and time, the effects of oceanographic parameters on sound propagation, seasonal variations in tidal currents, topography and sedimentology, and the physical chemistry of sea water. In support of its oceanographic effort, the Center operates the R/V ARTEMIS on long-term charter and has operated for the last three years the Navy research ship USNS SANDS (Figures 5 and 6). Center scientists have recently participated in joint efforts with New Zealand in KIWI

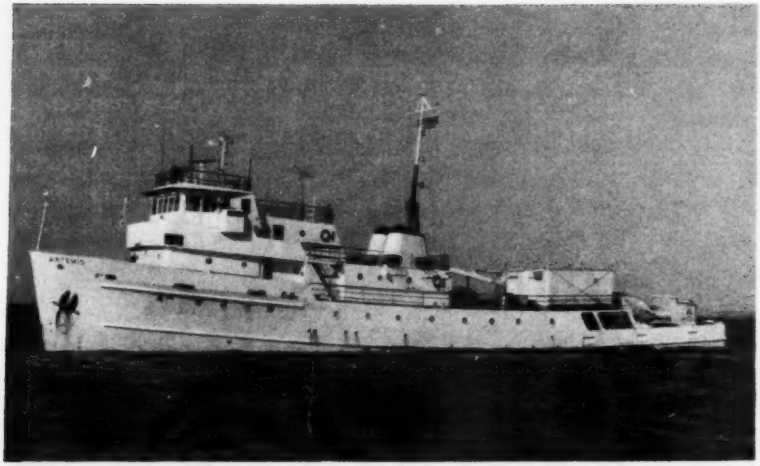

Figure 5–The Research vessel ARTEMIS, on long term charter to NUSC, began her duties with a cruise to the Hatteras Abyssal Plain in May 1973 with personnel from NUSC and the Lamont-Doherty Geological Observatory of Columbia University aboard. Other cruises have involved test deployments of a moored acoustic bouy system and participation in the Long Range Acoustic Propagation Project.

Figure 6–USNS SANDS (T-AGOR-6), with a civilian crew provided by the Military Sealift Command was assigned to NUSC in the fall of 1971 for use in underwater acoustics and oceanographic research programs.

ONE, investigating propagation loss in deep-ocean areas, and with the Lamont-Doherty Geophysical Laboratory in MAINLOBE (major investigation for low-frequency ocean bottom loss experiments). They have cooperated with such agencies as the Smithsonian Institution in Project OCEAN ACRE, a detailed study of the acoustic and biological characteristics of the deep-scattering layer in a one-degree-square area southeast of Bermuda, and the NATO Science Committee for Exploratory Research in Air/Sea Interaction in studying the variability in upper ocean layers in COBLAMED 1973. NUSC oceanographic work has resulted in a new model for the acoustic detection of objects buried in bottom sediments, an evaluation of a brine removal system which permits sampling of ocean cores without altering their chemical character, validation of mathematical simulation techniques for cable-moored oceanic buoy system design, and significant progress in armored cable design and engineering.

Since systems must be at-sea tested, NUSC has also been in the forefront in the field of underwater range technology. International recognition has come through its work in the research and development of underwater tracking ranges. The Center conceived and played a major role in developing the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahama Islands. NUSC has responsibility for the development of improved instrumentation and has full management control of the facility, the world's largest deep water range for undersea ordnance and acoustics systems evaluation (Figure 7).

Center experiments in acoustics and shallow water propagation loss are also carried out in range facilities in Long Island Sound. Still another outgrowth of Center range technology is the development and installation of the Barking Sands Underwater Range, Hawaii, for which NUSC maintains an advisory role.

In recent months, the Center has made important strides in utilizing its diverse talents and special capabilities to develop meaningful programs of technology transfer, environmental protection, and other nondefense-area efforts. The Center has established an Office of Special Programs Development to apply NUSC's multidisciplinary technology and resources to meet and solve urgent environmental and sociological problems confronting the nation. An active partner of the consortium of Department of Defense laboratories, NUSC is cooperating to match military-based technology to needs in the civilian sector at federal, state and local levels. Work in such areas as the analysis and evaluation of data on

Figure 7—For range exercises, in-air and in-water tracking data and impact prediction plots can be displayed in this weapons range control room at the Atlantic Undersea Test and Evaluation Center (AUTEC).

water mass movement, power plant and riverine sediment discharges, sea surface temperature, oil spill dispersion, shoreline changes, tidal marsh foliation, and mass transportation systems analysis bring the NUSC staff into close contact with other governmental and academic scientists cooperating to resolve mutual societal problems.

As the ability of man to move through and on the oceans has become greater, it has been more and more urgent that his ability to see and to communicate improves. At the same time, the need for new concepts in antisubmarine warfare is proportionate to the increasing number and capabilities of modern submarines and surface ships. In both cases, NUSC has enhanced the nation's defense capability, while it has made equally important collateral contributions to our understanding of the ocean environment and to the utilization of ocean sciences knowledge for nonmilitary purposes.

The Influence of Acoustics on Submarine Design

Walter L. Clearwaters*

(The Naval Underwater Systems Center has contributed significantly to the current state of the art in sonar research and development. The BQQ submarine sonar and SQS-26 surface ship sonar, which are the backbone of the underwater sensor systems in our modern submarines and surface ships, were both conceptual products of the Center. The Center's involvement has been and continues in such areas as acoustic propagation, transducers and arrays, the ocean sciences, and new system configuration. –W.L.C.)

The History of Submarines and of Sonar

The evolution of the submarine is itself an interesting subject, and there is no doubt that the influence of acoustics on this process may be seen in any modern submarine. However, one seldom pauses to consider that the evolution of a multi- million-dollar machine has been greatly affected by acoustic equipment whose cost is considerably less than that of the vehicle.

Man's interest in developing an ability to move about beneath the water for protection and secrecy dates back to ancient times. Early wall paintings from the Nile Valley show duck hunters creeping up to their prey beneath the surface of the water while breathing through hollow reeds. However, credit for the first actual submarine usually goes to Cornelius Van Drebbel, a Dutch scientist. His submarine, a leather-covered rowboat operating at depths of ten to fifteen feet, was demonstrated in England's Thames River about 1620. Throughout the seventeenth and eighteenth centuries an interest in submarine-like vehicles resulted in a variety of possible types. Then, in 1776, David Bushnell, an American colonist, developed the TURTLE (Figure 1). This submarine was armed with a keg of gunpowder; and the operator was supposed to pedal out to the target ship, attach the keg to the keel with a wood-screw auger arrangement, and fuse the charge. In the first recorded submarine attack on September 6, 1776, the TURTLE attempted to sink the British ship EAGLE, but the attack failed when the wood auger was unable to penetrate the copper sheathing on the keel of the EAGLE.

In 1800, Robert Fulton built the first NAUTILUS, a 21-foot copper-covered submarine. When his craft, with a top speed of only

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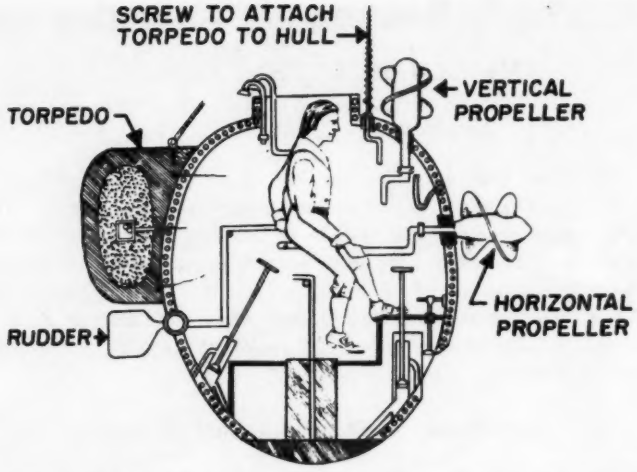

Figure 1 –David Bushness's TURTLE (1776) is credited with the first submarine attack. (Drawing courtesy of Submarine Library, General Dynamics Corp.)

two knots, was turned down by France, England, and the U.S., Fulton gave up and turned his attention elsewhere.

During the Civil War, the Confederate Navy developed several submarines called "Davids." One of these, the HUNLEY, made the first successful submarine attack when she sank the Union blockader, HOUSATONIC, in Charleston harbor. The HUNLEY was a converted steam boiler about 40 feet long and four feet in diameter. She was propelled by a hand-turned screw and had, under good conditions, a speed of four knots. Her complement was nine men, and her armament consisted of an explosive charge of 90 pounds of gunpowder at the end of a spar on the bow. During her career, she sank five times, the last of which was in the explosion that sank the HOUSATONIC.

The torpedo, the internal combustion engine, and the electric storage battery were key inventions leading to the first submarine commissioned in the U.S. Navy, the HOLLAND (Figure 2), launched in 1900. This 53-foot submarine displaced 75 tons, had a speed on the surface of 7 knots, and a cruising range of 1500 miles. However, until World War I the value of submarining remained uncertain. At the start of hostilities Germany had 28 submarines, with only 18 capable of distant wartime operations; the U.S. had a small force of which only 24 were equipped with diesel engines; and France had the largest subsurface fleet in the world, with a total of 67 submarines. But with the threat created by the effectiveness of German U-boats

Figure 2 –USS HOLLAND - the Navy's first submarine (1900)

against merchant shipping, the need for any and all means for countering the threat became urgent. From that time on, underwater acoustics has been a vital factor in submarine operations.

The history of underwater acoustics probably dates back many centuries to the natives of Ceylon who signaled between fishing boats by striking a submerged earthen pot and then listened to the resultant clink through the bottom of a boat miles away. In the late 1400's Leonardo da Vinci's scientific notes contained a passage on the use of underwater acoustics to detect distant ships.

The present era of sonar might be said to have begun with the development of the underwater navigation system produced by the Submarine Signal Company at the turn of the century. This system (Figure 3) was designed to provide mariners with continuous warning of the presence and location of navigational hazards. Large underwater bells were located at light stations along the coast. The bell, resonate at 1215 Hz, was detected by waterproofed microphones mounted in iron tanks fastened inside the hull plating on either side of the vessel. A switch arrangement allowed determination as to whether the source was to starboard or port. Typical ranges were 5 to 15 miles; and the success of the system was demonstrated by the existence in 1912 of 135 bells throughout the world and installations of receivers in over 900 vessels.

The Fessenden oscillator (Figure 4), patented in 1913, was used as an electroacoustic transducer capable of both transmitting and

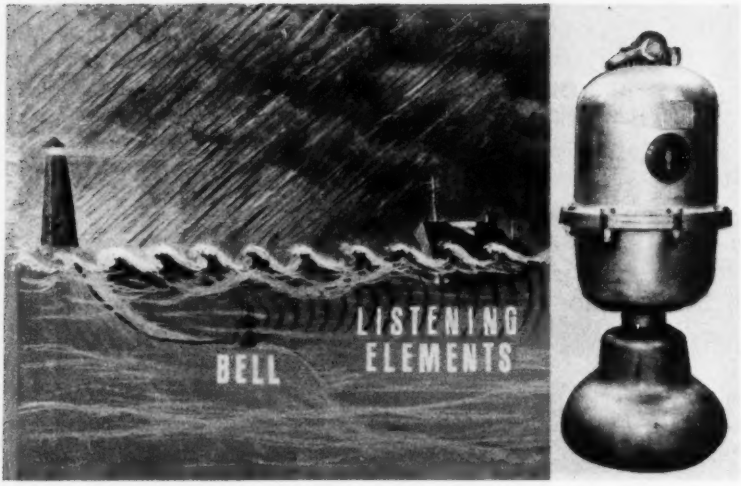

Figure 3 –Underwater navigation bell developed by the Submarine Signal Company was in fairly widespread use before World War I.

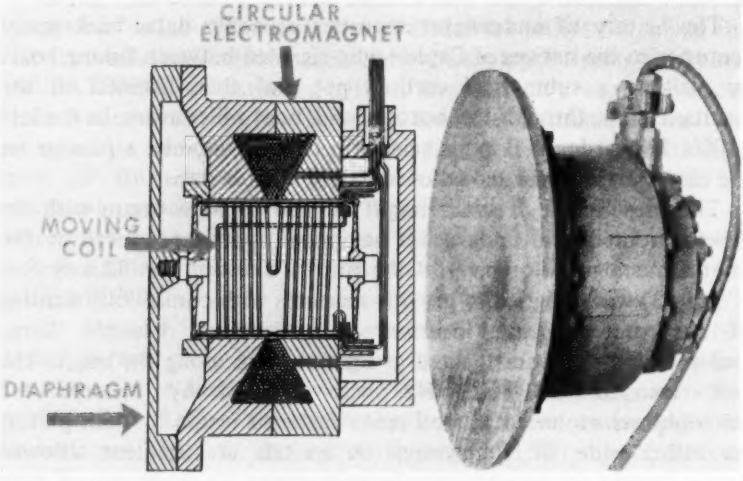

Figure 4 –Modified versions of this Fessenden oscillator, patented in 1913, were still in use in the 1950s.

receiving acoustic energy in the water. These oscillators came into widespread use in World War I, and modified versions were still in use in 1955.

At the outset of World War I, British research included the study of electric and electromagnetic fields associated with submarines, but their major effort was devoted to underwater sound. When the U.S. entered the war, there was an immediate mobilization of scientific effort. In July 1917 a meeting of several top scientists was called by Robert A. Millikan, then head of the National Research Council, to consider the antisubmarine warefare (ASW) problem. Among those present at this meeting, held at the Mohican Hotel in New London, Conn., was Max Mason of the University of Wisconsin. Mason consolidated his thoughts concerning the mechanically compensated line array, shown schematically in Figure 5. Within a week after the meeting, he was back in New London with a prototype which, despite its ungainliness, worked very well. The Mason line arrays which followed were, in practice, very large, approaching 50 feet in length, and contained hundreds of receiving elements. Even though they were awkward mechanical contrivances and limited by the size of the subchasers available to carry them, they worked well. These 110-foot long vessels had a maximum speed of 13 knots, obviously

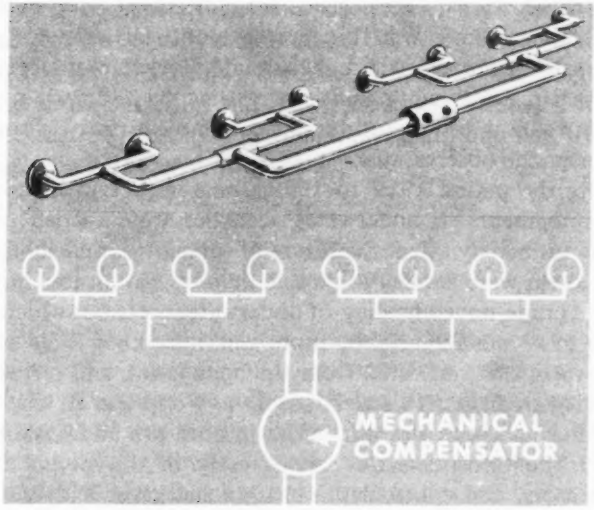

Figure 5—The Mason line array, conceived by Professor Max Mason of the University of Wisconsin in 1917, played an important role in early ASW.

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no match against the 18-knot submarine of the time. As the seriousness of the German U-boat threat increased, a special higher speed subchaser was needed to maximize the performance of the Mason line array. This need was fulfilled by the Eagle Boat, designed and constructed by Henry Ford.

One cannot help but be impressed with the results of the ASW development work in 1917 and 1918. In a brief seventeen months, there was produced the most successful detection device of the entire war. There was work on self-noise reduction, towed devices, explosive echo-ranging, and passive triangulation for locating distant sound sources. Other investigations included a lens for focusing underwater sound arrivals, and electrical compensators, which were further developed and later became key components for German passive arrays in 1939. Special purpose ASW subchasers had been designed and constructed; and research had been accomplished on piezoelectric resonators, hydrophone design, array principles, acoustic baffles, and even on submarine detection by magnetic and electrical means.

From the point of view of the influence of acoustics on submarine evolution, the years before World War II do not seem especially noteworthy. World War I had established the submarine as a major weapons system and underwater acoustics as a vital part of the ASW arsenal; however, the submarine remained essentially a surface vessel capable of occasional submergence for concealment and protection. At the start of World War II, submarines still carried deck guns for use against surface craft and antiaircraft guns to ward off attacks from the air. Sonar equipment was carried by submarines, but its importance was secondary to above-surface visual and electromagnetic observations.

During the period 1919 to 1939, some important investigations and developments in underwater acoustics were carried out, and these did ultimately affect the future of submarines and submarining. Among these were studies to determine propagation loss in the sea. The very crude understanding of underwater acoustics which existed prior to 1917 was replaced by more and more knowledge as to how sound propagated, reflected from the boundaries, and refracted due to velocity gradients. This work led up to World War II, where again, underwater acoustics was put to use in both pro and antisubmarine warfare. The antisubmarine arsenal early in this period included visual sensors, and mines, depth charges and guns. With the passage of time, the airplane, sonar, and radar became increasingly important; but none of these caused a major change in submarine design. However, minor changes were made in some features of

Fleet-type submarines to enable them tc cope better with these new adversaries. For example, to increase the ability of surfaced submarines to escape from surprise attacks by aircraft, submarine diving time was reduced. Strengthening of the pressure hull of Fleet submarines was also achieved to increase the survival capability.

During the war, submarines were provided with improved sonar equipment resulting from wartime R&D. German U-boats had an array of listening hydrophones mounted beneath the bow, with listening beams that could be trained by the use of electrical compensators. U.S. submarines carried mechanically trained listening hydrophones. Both sides had an echo-ranging capability, which was seldom used because of the risk to ones own safety. Other acoustic equipment was used to aid in communication, to provide signal intercept over a wide range of possible echo-ranging frequencies, to monitor own ship noise, to give depth-sounding, and so on. Both Germany and the U.S. developed acoustic homing torpedoes. The Germans also experimented with coatings on the hull to reduce the submarine's target strength against echo-ranging. From World War II on, the design characteristics of submarines have been more and more closely linked to capabilities in underwater acoustics.

The submarine started out as a weapons system against surface craft, and this is still a primary function. However, in World War II, U.S. and British submarines sank 65 enemy submarines and demonstrated their potential as an antisubmarine craft. In 1945 there is recorded a fully submerged attack by the British submarine VENTURER on a German submarine. This was the first case in which the entire detection and attack procedure was based solely on sonar information, used by one submarine against another, with both remaining fully submerged throughout.

Sonar and Submarine Development

After World War II, there were a number of attempts to develop special submarine concepts and equipment to capitalize on the potentialities of sonar as the principal submarine sensor. One of these programs involved converting some Fleet submarines to so-called "submarine killers" (SSK's). Various sizes and shapes of external sonar transducers were installed in assorted lumps and blobs; existing internal equipment and compartments were removed or rearranged to make space for a plethora of internal black boxes. Also the existing, and relatively primitive submarine noise reduction methods

were applied. At that time submarine noise reduction (we since have adopted the more confident nomenclature of "submarine silencing") consisted principally of trying to reduce radiated machinery noise by balancing or sound-isolating the installed rotating and reciprocating auxiliary equipment. In the first post-war conversion packages of our Fleet diesel submarines for snorkel operation, a sonar transducer was assigned a permanent place within the hull envelope. About 1950, conversions gave further status to sonar as a design factor by allocating a separate and special room for sonar operation and evaluation within the ship. This sonar room was very small, but it was of significant portent of things to come.

The "submarine killers" were designed and constructed to achieve their lofty aspirations through their superiority in sonar sensory and detection capabilities. The program was short-lived because the ships were unable to execute their ambitious mission due to inadequacies in submarine capabilities as well as in sonar. However, they did reflect an awareness that the submarine was itself becoming a principal enemy of submarines, rather than the classical concept of the surface ship being the principal or exclusive antisubmarine protagonist. This technique has been expanded and refined, until today the submarine has a major assignment in ASW. Thus, with regard to missions, the submarine has evolved from a platform for primary use against merchantmen to one which can also be used effectively in ASW. This change is the direct result of a capability to understand and to use underwater acoustics.

As regards hull form, there has been an evolution which allows greater submerged speed at the expense of surface seakeeping qualities no longer required by a submarine which can remain submerged indefinitely. Some of these changes are seen in Figure 6. The important points, acoustically, involve the use of more and more of the bow region to house the sonar because of the relatively low self-noise in this region. There is today a notable absence of topside guns, lifelines, antennas and masts, which beside producing drag, vibrate and raise the self-noise levels. Such effects may also be true of flooding holes and other necessary vents and cavities unless carefully designed.

Sonar came to maturity as a first-magnitude submarine design factor with USS THRESHER (SSN 593), authorized in 1957 and commissioned in 1961. The basic design of this attack submarine was affected to a large degree by requirements stemming directly from sonar considerations. The size, pressure hull geometry, and internal space arrangements were designed to allow sonar equipment and systems first choice of the ship's space. The desire to reduce the

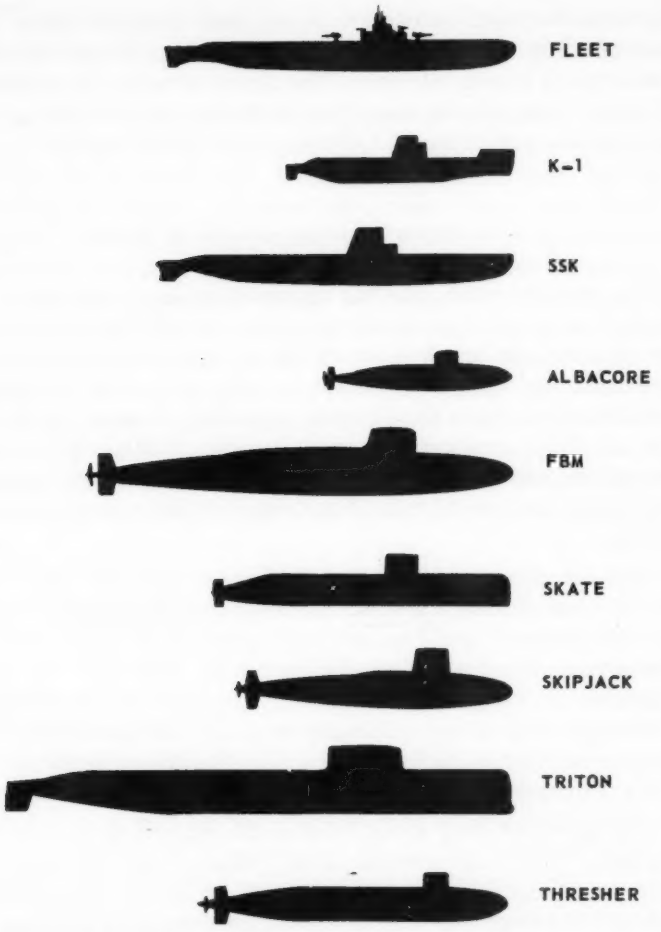

Figure 6 –Hull configurations of representative submarines since 1940.

submarine's radiated and self-noise to the very minimum was reflected in propulsion design features, as well as in the auxiliary equipment specifications. Tactical and fire control spaces were arranged and located so that the preferred method of weapon delivery could utilize sonar as the primary tactical sensor.

With THRESHER antisubmarine sonar considerations became major factors in submarine design. Significant effects on the size and internal arrangements of these submarines can be traced directly to the desire for avoiding detection. The streamlined hull form coupled with the axially mounted, single propeller stemmed principally from

the need for high submerged speed and maneuverability. These features also contribute to the inherent effectiveness of the submarine as a sonar platform. The desire to reduce the submarine's self-noise and radiated-noise has motivated the continuing design development and refinement of that hull/propeller concept.

The Modern Submarine and Its Sonar

The modern submarine has an extensive sonar suit, which is the single most expensive item of electronics aboard. The growth in deck area and volume required for all electronics equipment has steadily increased. By way of comparison, the post war diesel-electric submarines had more than double the area and volume of the World War II Fleet submarines; and for the THRESHER class the proportion was still higher. The following table shows comparative figures for sonar suits for the World War II and the current submarine classes.

	WW II	CURRENT
Volume	325 cu ft	520 cu ft
Weight	10,400 lb	45,000 lb (electronics) 240,000 lb (arrays)
Cost	$87,000	$8,000,000

The spherical array in the bow of the modern nuclear submarine contains 1245 separate elements, which may be used in an echo-ranging mode or for passive tracking of targets. Wrapped around the bow is a large conformal array for low-frequency listening. Other sensors for various purposes are mounted along the hull. Obviously, the bow of this submarine has been given over to sonar because this location provides the lowest self-noise interference, especially at higher speeds. This sonar sensor location necessitated relocation of the torpedo tubes further aft. Sonar thus dictated a major weapons change and required the solution of the special problems which result when torpedo firing must be done from angled tubes.

Internally, a forward space houses more than 25 six-foot cabinets of equipment, and a sonar room amidship houses control consoles. When fully manned, the sonar requires six or more operators, to say nothing of coordinators, plotters, and conning officers who must assess incoming sonar data to derive the necessary maneuvering and

firing information. In addition, a complement of specially trained personnel are required for maintenance and repair of this complex sonar suit.

Underwater acoustics has also played an important part in the evolution of submarine weaponry. The straight- running torpedo was a marvel of its time; and submariners became quite skillful in estimating the course and speed of a target from which could be determined the future target position at the time of torpedo arrival. These earlier models have been replaced by torpedoes which can be used at longer ranges and which will search out the target either passively or actively at the appropriate time in their run. The SUBROC weapon may be fired submerged, will follow a path through the air-water interface, and then reenter the water many miles away at the target position. Since the submarine commander does not see his target in the case of either long-range torpedoes or SUBROC, the entire success of these weapons depends on detection, classification, and attack solutions based on acoustic information alone.

Probably the most vital of all matters, as far as the submariner is concerned, is his ability to use the ocean as a place to hide. This was the motivating force with the original duck hunters and their underwater approach, and it remains so today in the most modern submarine. If his adversary is using echo-ranging, the submariner wants to know it; and since he cannot change his target strength, he wants to position himself most advantageously in depth and relation to any natural surroundings which may help to protect him. This he can do only as well as his understanding of underwater acoustics allows. An evolution in submarine tactics has followed from the increase in our state of knowledge of underwater acoustics.

Evasion from echo-ranging vessels is generally considered an easier problem than that of avoiding vessels using passive detection, because, in most cases, the submarine has a detection range advantage over the echo-ranger and places himself in a position that would return an echo only as a calculated risk. But then, having taken the risk (or even worse, in the passive case, when he does not know he is in danger), the submariner becomes concerned about his own acoustically radiated noise.

Vulnerability to detection by underwater passive sonar devices has been for a long time an important factor to be considered in submarine design. In fact, one wonders how Bushnell in his TURTLE in 1776 expected to get away with boring a hole in the bottom of a ship without being heard.

The use of direct-drive electric motors for submarine propulsion is important because it eliminates reduction gear noise. The Germans used a method of bypassing the reduction gears by employing a belt drive to the propeller shaft for low-speed, submerged, quiet operations. Submariners are concerned about dishes rattling, interior communications noise, and the noises men make while walking through the submarine. Naturally, all auxiliary machinery noise and certainly main power plant and propeller noise is of prime concern, and as submarine speeds increase and power plants get bigger, this kind of radiated noise is given serious design attention. One can certainly say that the evolution of propulsion machinery within the submarine is vitally influenced by acoustic considerations.

Future Goals

The submariner is not yet satisfied. Future goals involving underwater acoustics are: better communications, especially between mutually supporting submarines; better and more precise fire-control solutions; better navigation; better weapons, with less susceptibility to acoustic countermeasures; and better, more complete, integrated system designs in which the acoustically derived information is more effectively used. Also, as the amount of equipment increases, reduction in size and increase in reliability are vital.

Just as underwater acoustics is having a profound effect on submarines and submarining, so, also, is the submarine in both its use and its threat having an important effect on environmental investigations. As fast as new and more detailed information about underwater acoustics is available, it is absorbed by one or another of the many potential users, either for, or against, submarines; and there are continuous requests for more. Unfortunately, the customers all too often balk at the price of such investigations, especially when this is in terms of ship time at sea, or new and expensive special-purpose facilities.

However, progress in developing better research facilities does take place. These facilities, their use, and the information they obtain will certainly point the way to further evolutions in submarines. Investigations of the characteristics of water flow over the submarine hull and of the interfering noise fields have been conducted in special-purpose air and water tunnels using special instrumentation. More definitive knowledge of these phenomena can be used to optimize sensor location, and signal processing equipment can be designed with better discrimination against flow noise at high speeds.

There seems little doubt that future submarine evolution will include designs for operations at greater and greater depths. One can only guess at the ultimate military potential resulting from investigations by such craft as the research vessels TRIESTE, ALBACORE, and DOLPHIN (Figure 7); but the research importance is without question. All of these deeper-diving vehicles depend on acoustics as primary sensors which must provide for communications, navigation, station-keeping, and all other information from the outside.

A brief mention of peacetime and futuristic roles for submarines seems appropriate in closing. The expanding world population will probably accelerate the necessity to obtain vast quantities of food and other mineral products from the sea. Men will have to learn to live in the sea through investigations and experiments such as the "Man-in-the-Sea" program (Figure 8). Habitats will probably be established at even greater distances from the shore; and as the men desire to roam further and further from these habitats, submarine-like vehicles will certainly be involved. The concept, itself, depends on the use of acoustics as the only means of effective underwater information exchange, be it for communications, navigation, or simply, returning home with a high degree of precision and confidence.

Figure 7–Research submarine USS DOLPHIN during an assignment to NUSC, 1969.

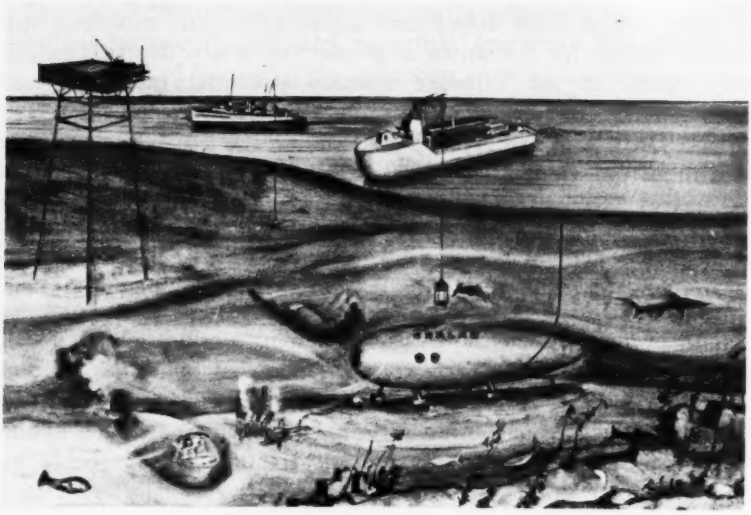

Figure 8 –Artist's conception of typical underwater research habitat in a working environment.

Certainly these concepts and other peacetime and military uses of submarines will be even more directly influenced by underwater acoustics in the future than has been the case in the past, and sensor systems will continue to have a major influence on submarine designs.

Eye Sampling Study

To model the sonar operator observing a visual display, the operator's procedure for obtaining data from the display must be determined. It is necessary to know how the operator samples the display must be determined. It is necessary to know how the operator samples the display and the effect of display parameters on this sampling. Patterns in the sampling procedure, the uniformity of display sampling, and the data actually observed on the display must all be known.

Some answers to these questions are now available from studies, being conducted by Dr. R. L. Mason at the Naval Underwater Systems Center, of sonar operators observing PPI and other displays involving target identification.

(Continued on page 32)

Shipborne Combat System Integration

Earle L. Messere*

A combat system is a complex of shipborne warfare equipment that allows a ship to engage targets for both offensive and defensive mission situations. The typical combat system consists of the following discrete subsystems:

Sensors	Exterior communications
Fire Control	Weapon and countermeasure devices
Navigation	Launching and Handling
Surveillance	Ship Control
Command	Interior communications

The integration of such a generalized combat system is a necessary continuing process in the developmentof military ships.

System Integration

A *system*, as defined by military specifications, is a composite of equipment, skills, and techniques capable of performing and/or supporting an operational objective. A complete system includes all equipment, related facilities, material, software, services, and personnel required for its operation and support to the degree that it can be considered a self-sufficient unit in its intended operational environment. Similarly, *system engineering* may be defined as the application of scientific and engineering principles to transform operational requirements into a description of system performance parameters and a system configuration/specification through the use of an iterative process of definition, synthesis, analysis, design, test and evaluation. The criteria used in analysis, test and evaluation are the dominant factors in the acceptance or rejection of the many alternatives in this iterative process. As such, *system integration* is a subdiscipline of system engineering which concerns itself with the combining of independent parts of system elements into a more complete harmonious whole with improved system characteristics relative to its intended operational use.

*The author is Head, Combat Systems Control Department, Naval Underwater Systems Center

The typical system includes a variety of independent elements or subsystems. Such a system cannot operate as a whole without an application of system integration techniques during its development. The great variable in system integration is the degree to which it is applied, from minimal with little benefits to excessive with system degradation.

Criteria for Analysis, Test and Evaluation

Since integration is a subdiscipline of system engineering, its application to system development is accomplished by adding specific integration factors to the criteria for analysis, test and evaluation during the iterative process of system engineering. It is quite common in system engineering to use performance, cost time, maintainability and reliability appropriately weighted as the criteria for accepting or rejecting configurations during the synthesis iterations. Of course, performance includes constraints such as size, weight, power, man-machine relationships, and military standards for environmental conditions. The principal additional criteria for integration are total life cycle support, commonality of operational man-machine interfaces, flexibility, adaptability and growth potential. More specifically these criteria involve the following objectives:

Minimize kinds of equipments.
Minimize numbers of equipments.
Minimize number and kinds of interface problems.
Standardize on military environmental specifications.
Standardize on configuration control documentation, publications, reliability, maintainability and training.
Standardize computer software architecture.
Adopt flexible system architectures.
Provide growth margin and redundancy.
Standardize on operator inter-active displays and controls where possible.

These objectives when added to the previously mentioned criteria (with proper weighting as additional forcing functions to the system synthesis as depicted in Figure 1) can yield significant reductions in space, weight, acquisition costs, support costs, operator personnel numbers and skill levels, cost and time of future add-ons without performance degradation of the system as a whole. In the case of a heavily manned system there can be an improvement in system performance by achieving a more cohesive total system "team."

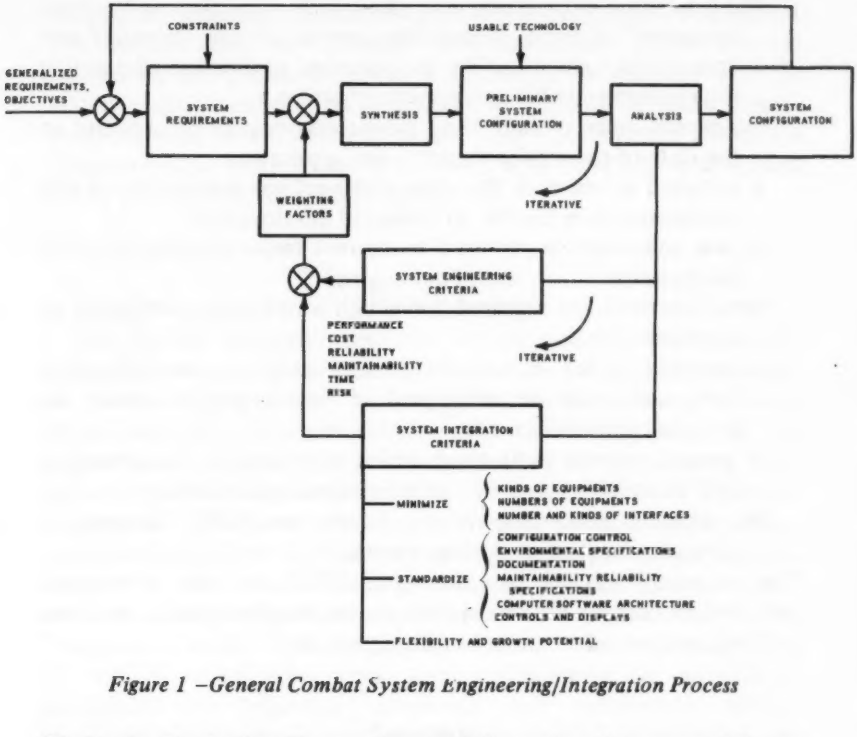

Figure 1 –General Combat System Engineering/Integration Process

Obviously, the trade-offs must be carefully analyzed to prevent "over integration" which could yield an unacceptable degradation of performance.

Baseline

The starting point, or baseline, is a significant variable affecting the approach to system integration. The two extremes are (a) no usable subsystems or devices exist at the start of the program, or (b) all subsystems exist at the start of the program but require modification to operate as a unified whole. For various reasons, combat system integration almost always starts with a baseline somewhere between these two extremes. These reasons may be summarized as follows:

The combat system consists of highly specialized subsystems.

Many of these subsystems already exist with adequate conformance to system criteria and modification or use "as is" is more cost effective with minimal risks (new production may be required).

These existing subsystems are often fully qualified as "Service Approved" (having successfully passed formal technical and operational evaluation) for the intended application eliminating the requirements for costly requalification.

Functional areas of individual subsystems require an advance in the state-of-the-art for the intended application.

A required advance in the state-of-the-art has been achieved and demonstrated as feasible in advanced development.

A new subsystem is required to correct major deficiencies in its predecessor.

New functions are required for which a new subsystem must be developed.

A required device or technology may exist in a nonmilitarized form and must be redesigned or repackaged to satisfy the intended application.

A general-purpose militarized device may exist in the inventory that is usable for a variety of subsystem applications.

An existing subsystem is no longer producible because of specialized out-moded components.

This necessary mixture of existing, modified, and new subsystems and devices complicates the system engineering/integration problem and requires special treatment in the approach.

Approach

The general requirements must be analyzed from a total system viewpoint and translated into system requirements as shown in Figure 1, indicating the types of subsystems required. These system requirements, along with constraints and criteria, are then allocated to subsystem managers, who prepare individual Proposed Technical Approaches (PTAs) for their subsystems including several candidate alternatives with qualified preliminary characteristics with respect to the assigned criteria for analysis. This is a system engineering/integration process applied to the subsystem and is referred to as "vertical" integration.

The system manager uses the preliminary subsystem PTAs and performs analysis and synthesis with respect to the judgment criteria and arrives at a preliminary total system PTA. This entire process is iterative until a finalized PTA is achieved.

The resultant configuration can be considered a "federated system." This process is then extended to achieve total system and subsystem specifications including partitioning and interface

definition necessary to proceed into development and acquisition. The specification, development, and acquisition phases are not treated in this paper, however, it cannot be overstressed that the system engineering/integration process, as depicted in Figure 1, must continue well into the design phase. This continuation allows the reassessment of early trade-off decisions with more quantitative data in the area of cost, schedule, logistics, etc.

Integration Issues

The system manager/integrator, during analysis and synthesis, identifies functional areas which are candidates for merger where two or more subsystems can be supported with common services; employment of common hardware called "integrating elements" for two or more subsystems; and standardization of data formats. This inter-subsystem integration process is referred to as "lateral" integration. This process results in system partitioning, interface definition, allocation of functions, space, weight, power services, etc. Because of the valid conflicting interests between subsystem and integration objectives this process leads to what are often called "integration issues." Some examples of these issues include merging of smaller subsystems into larger subsystems vs separation; centralized vs dedicated computers and peripherals; system partitioning boundaries; use of standard integrating elements (such as digital computer and peripherals, digital interactive displays, analog, digital and digital/analog converters, bulk data storage devices, executive computer software, information transfer devices, switchboards for power and data, recording devices, data formats and transmission schemes, system architecture, signal processors, and documentation formats); characteristics of newly developed integrating elements; definition of interfaces and installation procedures and arrangement layouts.

Integrating Elements

When an integrating element is to be used in more than one subsystem it must be selected or developed with special constraints: its characteristics, including logistic support, must satisfy the varied requirements of all its users; its reliability and maintainability must be developed and demonstrated on a device basis because of its varied employment; its characteristics must be defined early in the

synthesis cycle to allow analysis of its impact on subsystems; it must be made available soon enough for subsystem integration; and its configuration management must be executed on a cooperative basis with participation of all intended users.

Integration Testing and System Certification

Because the entire system must perform as an integrated whole in its intended environment and the cost of ship construction as a test bed is prohibitively high, mock-ups, installation models, land-based test beds, and prototype testing on similar existing platforms are used to minimize the risks and reduce the cost of installation and checkout.

The land-based test bed provides the opportunity to connect most of the subsystems into an integrated whole to permit integration testing, modification, an early warning of ship installation problems, and preliminary system certification. The test bed is configured as a partial replica of the ship and its operational environment, utilizing simulation and stimulation, where practicable, to represent the interfaces and subsystems not amenable to inclusion in the test bed.

Each of the subsystems is certified before delivery to the system test bed and as such the objective of integration testing is to demonstrate that the allocated performance for each subsystem is not degraded when operated in concert with other subsystems. The objective of certification is to demonstrate that the system, as a whole, satisfies its requirements when evaluated in its simulated operational environment. As such, certification can be considered as a preliminary technical evaluation.

The treatment of Shipborne Combat System Integration presented above reflects the author's experience over a number of years. It represents a methodology of engineering and management that has been applied in several development programs and as such is somewhat matured by experience. Its principles, when properly applied, offer a powerful tool for the synthesis of complex systems from a total life cycle cost viewpoint.

Atlantic Undersea Test and Evaluation Center

J. J. Greichen and J. F. Milne*

Located in the 100-mile long Tongue of the Ocean, east of Andros Island in the Bahamas, the Atlantic Undersea Test and Evaluation Center (AUTEC) has served, since 1966 as a deep-water test and evaluation facility for making underwater acoustic measurements, testing and calibrating sonars, and providing accurate underwater surface and air tracking data on surface ships, submarines, aircraft, and weapons systems. The facility, the first of its kind in the world, was constructed by the United States on agreement with the Bahamian Government and Great Britain.

In addition to being responsible for the concept, design, installation and certification of the weapon range in 1966, the Naval Underwater Systems Center (NUSC) since July 1971 has had principal development agency responsibility for AUTEC, involving command and overall management operation, support, and continued development. NUSC maintains two detachments in the area: one at West Palm Beach, Florida, providing logistic support, range scheduling, and range-user liaison; and one at Andros Island, the range site. AUTEC is a complex of three measurement ranges: a weapons range a Fleet Operation Readiness Accuracy Check Site (FORACS), and an acoustic range. (See Figure 1.) The facilities provided by AUTEC are both useful and necessary for realistic exercises to maintain Fleet readiness and current state-of-the-art research and development posture.

The FORACS determines the accuracy of surface ship sonars radars, peloruses, fire control systems, and gyrocompasses. AUTEC's weapons range provides research and development and Fleet communities with instrumented facilities to conduct antisubmarine warfare (ASW) weapon system evaluation and to develop and assess ASW tactics. The acoustic range detects, records, and perfoms measurements on surface ships and submarines. This range is also capable of tracking a vessel under test and recording data, thereby permitting the necessary attenuation corrections to be applied. In addition, an advanced sonar range, also shown on Fig. 1, will give the

*The authors are members of the Test and Evaluation Directorate of the Naval Underwater Systems Center, where Mr. Greichen is AUTEC Program Manager and Mr. Milne is Sonar Range Program Manager.

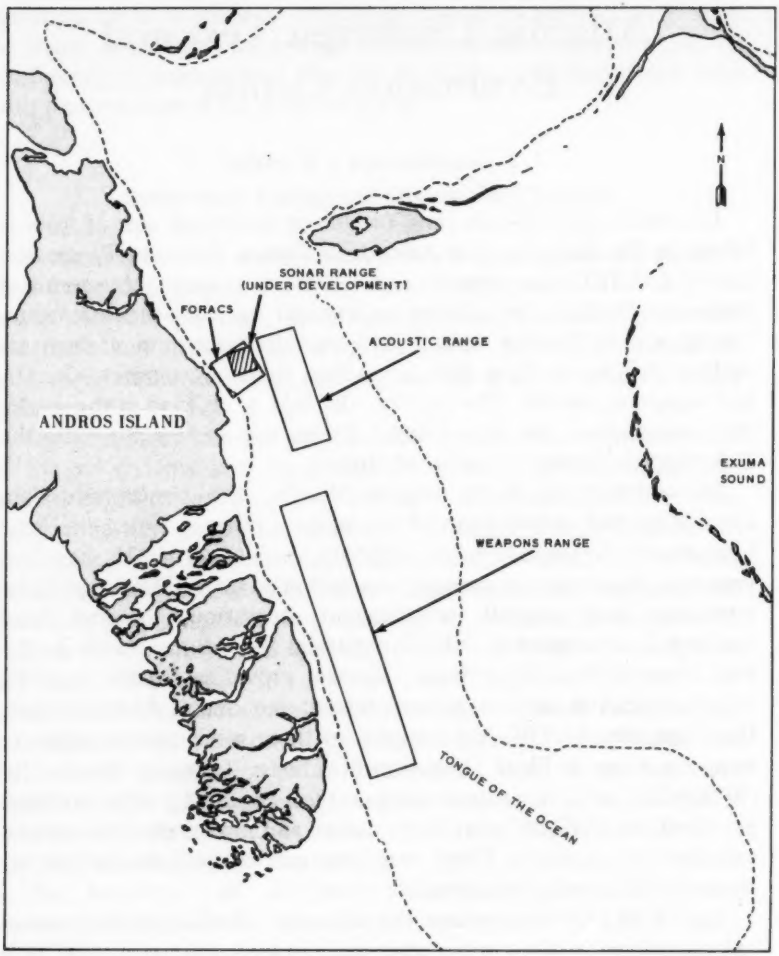

Figure 1 -AUTEC ranges

Navy a unique capability in verifying ship sonar under realistic conditons.

Center research and development efforts aim at continuously increasing AUTEC capabilities in such areas as sonobuoy tracking, passive tracking, data analysis techniques, and weapon range software. Among recent developments, for example, improved pinger systems give the AUTEC range a greater flexibility in the number and types of targets that can be simultaneously acquired and tracked. A new sonar transmitter, smaller and cheaper than earlier pinger

electronics, requires no synchronization, no connections external to the weapon, and no trained technicians aboard ship during exercises. This new pinger can also be used to track multiple targets on the same frequency by means of selected repetition rates. Another innovation, called STEP (for shipboard tracking electronics, portable), permits tracking of any surface ship or submarine equipped with an appropriate projector capable of emitting the acoustic format for the ranges. STEP requires no costly and time-consuming hull modifications or projector mounts. In another development, the structures and cables for an improved acoustic noise measurement array in the AUTEC acoustic range are being implemented.

The research and development work NUSC conducts for Fleet support at AUTEC is typified by the sonar range development program currently under way. The sonar range will consist of three subsystems: underwater, shorebased and shipboard. New sonar system concepts and their hardware implementation require the use of existing theory and mathematical models, and uncertainty exists because approximations are necessary. Therefore, empirical data of adequate accuracy must be gathered in a timely and economical manner to verify analytical development.

Although facilities do exist to gather empirical data, the sonar range offers a unique capability to gather data in the operating environment on the dynamic interaction between the medium, the sonar platform, and the sonar system. The major function of the sonar range is to provide accurate data on the transmit or receive sonar beam patterns for any steering angle and (in the case of a submarine) operating depth. In addition to the beam patterns, the sonar range will measure source level, receive sensitivity, and steering accuracy of the sonar beams.

Beam patterns are important because they provide for the expected sonar performance. Accuracy of target tracking and weapon delivery is directly dependent on knowledge of beam steering, and the horizontal beam patterns. The measured beam patterns should include all affecting factors such as ship structure, dome, bubble sweep-down, steering angle and (in the case of submarines) operating depth.

The underwater system receives or projects sonar test signals and also receives tracking pings from the test vessels on the range. The shorebased system processes the received sonar and tracking data and generates the sonar signals to be transmitted. The portable shipboard system is onboard only while the vessel is on the range. This test hardware accurately measures and records the attitude of the vessel

and records data of interest from the ship's sonar system, for post-operational analysis. the equipment consists of a vessel-attitude measurement unit, analog recorders, and the electronics to generage the tracking signals.

In addition to the sonar range development program NUSC is studying the advantages and limitations of mobile ranges. The intent of these studies is not to develop a specific configuration, but rather to investigate the needs of the Navy and to relate them to the developing state-of-the-art capabilities and requirements will lead to cost effective solutions.

With AUTEC, the Navy's largest and most advanced underwater test range, the Naval Underwater Systems Center provides important support for the Navy's antisubmarine warfare and undersea research and development programs and for ASW Fleet assessment and operational readiness.

(Continued from page 22)

A sonar operator's eye fixation are obtained from an electrooculargram (EOG) recorded while he is observing the display. The EOG is a record of the electric field around the eyes obtained from skin electrodes. This electric field, caused by a constant potential difference across the eyeball, changes as the eye rotates in its socket. Thus, the angle of the eye can be obtained from the EOG, and the location of the operator's fixation of the display can be calculated from the angle.

The greatest difficulty with this type study is in the analysis of the large amount of data which is obtained in an experimental session. This difficulty is partially overcome by the use of computer data processing. A procedure for estimating the fixation point has been developed which reduces the data storage requirements, smooths the data, yet maintains the rapid change in fixation points characteristic of eye movements.

Analysis of sonar operator eye fixations on PPI and DIMUS displays has shown:

(1) Visual sampling of a display is not uniform. Operators make no fixations in some areas, but many fixations in other areas.
(2) Sonar operators rely on non-foveal vision in searching a display. The visual angle used for search subtends 4 to 5 degrees, but the foveal vision subtends less than 2 degrees of visual angle.
(3) The average eye fixation is 0.23 seconds long but most viewing time on the display is in fixations ranging from 0.2 to 0.4 seconds.
(4) Targets and possible targets are fixated.
(5) Compared to untrained personnel, sonar operators are very good at the detection tasks given them.

Diverless Helicopter Weapon Recovery System

John R. Hinves and LCDR Robert W. Klementz*

Among its most significant recent accomplishments, the Naval Underwater Systems Center (NUSC) has successfuly developed, tested, and evaluated a safe and speedy helicopter recovery system for vertical floating exercise and dummy torpedoes. The diverless helicopter weapon recovery system (DHWRS) utilizes a rigid aluminum cage which is lowered over the nose of a vertically floating torpedo from a hovering helicopter and then hoisted to a horizontal attitude so the weapon can be swiftly transported to the turnaround or transport area. As implied by the name given the program, the DHWRS does not require any personnel in the water or on a raft for the alignment and attachment of the lifting or transporting gear to the torpedo.

The Navy has traditionally captured and recovered expended torpedoes and torpedo targets through the use of various types of small retriever craft of medium to high speed. With these, the expended torpedo is captured by means of a line and hook or some type of capture device. The retriever craft is backed into the vicinity of the floating expended torpedo, which is in either the vertical or horizontal attitude, and the torpedo is winched aboard up an inclined plane. Difficulties in retrieval were encountered in rough seas, and safety of personnel aboard the retriever craft often proved marginal. Recovery itself was time-consuming. Furthermore, transit time from range to base with the retriever proved too lengthy for effective and economical range use. With the advent of newer torpedo weaponry and increased weapon firing density rate on the ranges, this factor became critical.

In 1970 a helicopter/diver system was designed to meet immediate Navy needs at the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas and proved the superiority of recovery by helicopter over that by small craft retrievers from the point of view of decreased chance for physical damage to the weapon and reduced overall transit time for return to the weapon shop for

*Mr. Hinves is Launcher Program Manager and LCDR Klementz, currently assigned as Executive Officer aboard USS RIGEL, is the former AUTEC Military Program Manager at the Naval Underwater Systems Center.

Figure 1 -Seconds after retrieval of exercise torpedo from tne water, the weapon recovery cage and its cargo are enroute to the land station. The retrieval operation with this diverless system averages under one minute.

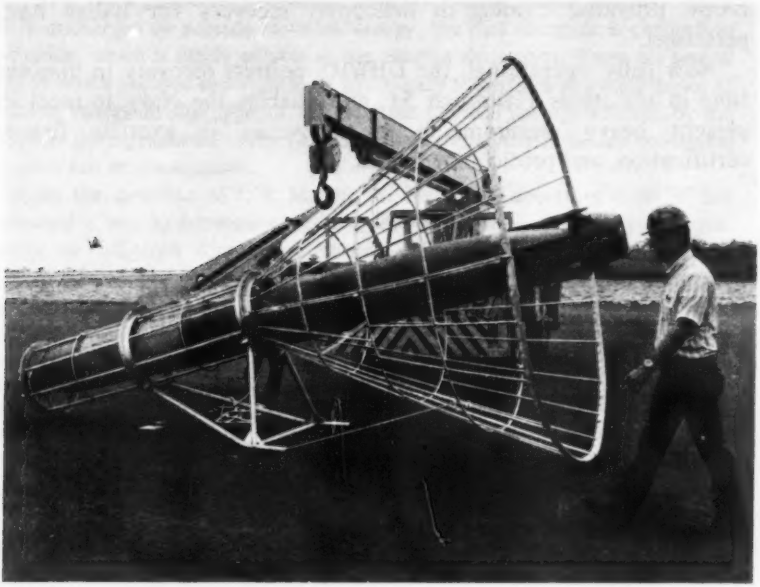

Figure 2 -Within minutes the torpedo is landed and ready for shore facility handling. The ferrying helicopter can be seen (left background) departing the station area for another exercise recovery. The cage is so constructed that surface abrasion or other damage to the torpedo casing (sometimes an aggravating problem with retriever-boat recovery) is negligible.

recycling. Although a vast improvement over boat recovery, this system was still time-consuming (5-minute average for recovery) and still inherently dangerous to personnel by requiring diver/technicians in the water for torpedo capture. These factors, together with the system's need of a specially prepared landing area, dictated continuation of the search for an improved method. NUSC therefore concentrated on developing a system which did not require a diver in the water and which had a self-contained landing apparatus.

Following system exploratory tests at Newport and Pt. Mugu, in late 1972, a series of development/evaluation tests were run at AUTEC with an average recovery time of 3 minutes. During early 1973 at AUTEC, operational recovery was effected during a torpedo training exercise in under one minute in sea state 2. This was a significant milestone in the development of open sea recovery capability for Fleet units.

The system is also being employed in operational recoveries at the Pacific Missile Range Facility (Barking Sands), Hawaii. In addition,

NUSC provided training in helicopter recovery for Italian navy personnel.

Now fully operational, the DHWRS permits recovery in minimal time in sea states 1 through 5+, and enables the Navy to meet its present heavy requirements of recoveries in exercise firings, certification, and proficiency firings.

Elastomer Bonded Zinc Dust Electrodes for High Rate, Secondary, Zinc-Silver Oxide Batteries

The zinc-silver oxide cell has a higher energy density than any other commercially available secondary (rechargeable) cell. However, the cell is expensive, making it worthwhile to investigate and upgrade the weaker components. In this regard, an area of recent study at the Naval Underwater Systems Center (NUSC) has been the electrodes and their individual contributions to the cell.

Of the two electrodes, the zinc electrode is much less stable than is the silver oxide electrode. The former tends to react with the highly alkaline battery

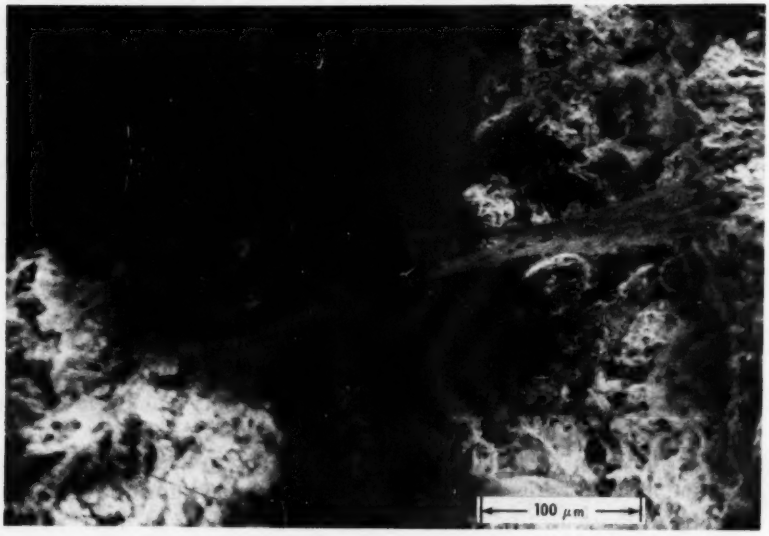

Figure 1 –This photomicrograph, taken with a scanning electron microscope, shows how the elastomer holds the zinc particles to the grid structure in a zinc plate from a cell that has been cycled 20 times. The electrodes are made using a technique for which NUSC has filed a patent application.

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electrolyte (40% potassium hydroxide solution). Further, as the zinc-silver oxide cell is discharged to provide electrical energy, the zinc electrode is changed to zinc oxide, which is highly soluble in the alkaline electrolyte. There are several ways in which the zinc electrode loses its capacity to perform as a contributor of electrical energy in this type of cell, and the physical damage suffered by the zinc plate during repeated cycles (discharges and recharges) of the cell containing this plate can be considerable.

Under the direction of J. R. Moden, the Materials Laboratory at NUSC has discovered a way to fabricate zinc electrodes which are not so easily damaged. Testing in full-sized torpedo propulsion cells has demonstrated that the NUSC-produced zinc plates show essentially no damage after repeated discharges and recharges. The NUSC zinc plates were made by mixing a small amount of neoprene latex (a synthetic elastomer in liquid form which dries to a rubbery substance) with zinc dust. This mixture is spread and pressed onto a silver screen-like grid, then dried, and the electrode plate is complete. The elastomer helps to hold the particles of zinc dust together.

Initial support for the development work to upgrade the zinc electrode was derived from the Center's Independent Research fund. The improved electrode has provided a way to extend the cycle life of zinc-silver oxide cells. This additional cycle life can be translated directly into higher reliability of batteries and into dollars saved.

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Note:

These materials have been assembled and edited by Dr. Lionel D. Wyld, Code LA12 (Special Projects Staff), Naval Underwater Systems Center, Newport, R.I. 02840.

Cover Caption:

The cover photo shows one in a sequence of stroboscopic holograms of a section of a steel SQS-26 sonar dome. The sequence of holograms yields the amplitude and phase of the vibration of the entire section. The dome was acoustically excited in water at frequency in the operation band of the system. The grid lines were printed on the surface to indicate the position of framework behind the surface. The work was conducted at the Naval Underwater Systems Center.

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